

# RESIN INFUSION MOLD TOOL SYSTEM AND VACUUM ASSISTED RESIN TRANSFER MOLDING WITH SUBSEQUENT PRESSURE BLEED

## 5                    FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

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## 10                   FIELD OF THE INVENTION

The present invention relates to the fabrication of composite structures, in particular the fabrication of composite structures using a tool assembly to support a dry fiber preform and vacuum assisted resin transfer molding to infuse resin into the dry fiber preform.

## 15                   BACKGROUND OF THE INVENTION

The production of large and complex fiber composite structures, such as airplane wings, requires critically dimensioned features to be held within narrow tolerances. Until recently, process for the production of large and complex fiber composite structures did not exist. Large and complex structures had to be broken down into multiple pieces of a more simple design. Each piece was produced individually and then assembled to create the larger structure in a labor-intensive and costly process.

The development of resin film infusion (RFI) methods and the mold tooling used with RFI methods, as demonstrated in U.S. Patent No. 5,902,535 to Burgess et al., has allowed the production of composite structures up to 70 feet in length. The RFI process involves placing a resin film directly in between, and in contact with, the dry fiber preform and the mold tooling. The mold tooling, resin film and dry fiber preform are then vacuum bagged and inserted into an autoclave. As the temperature and pressure in the autoclave are increased, the resin film melts and is infused through the preform. Large displacements of the mold tooling and fiber perform are not uncommon when thick resin films are used in the RFI process. Large displacements

5 of the mold tooling and the fiber perform can adversely affect the dimensional tolerances of the resulting composite structure.

Vacuum assisted resin transfer molding (VARTM) has also grown over the past few years to include the fabrication of large composite structures for the marine industry, as well as secondary structures for military aircraft, such as engine inlet  
10 ducts. In VARTM the liquid resin is infused into the preform by pulling a vacuum on the mold tool. The liquid resin is introduced to the preform with inlet tubes and a manifold system located on the outer surface of the preform. The liquid resin is drawn through the preform via the vacuum pressure. In VARTM, the mold tool requires only slight movement to compensate for bulk reduction in the preform as the  
15 vacuum is applied.

Many VARTM structures, however, fail to meet the more stringent structural criteria required for primary structures in aircraft. Primary aircraft structures must have a fiber volume fraction in the range of 57% to 60%. Fiber preforms with thick cross-sections, typical of aircraft primary structures, require significant force  
20 application to remove bulk and raise fiber volume fractions to acceptable levels. The fiber volume of thick structures is typically less than 54% due to the relatively low pressure vacuum provided during the VARTM process. In addition, parts made with VARTM are typically relatively simple in design and have a minimal amount of integral structure. The inner mold line is shaped using a soft rubber or nylon vacuum  
25 bag, with very little being done to hold the critical dimensions on the mold line surface.

As an alternative approach, U.S. Patent No. 5,441,692 to Taricco discloses a process for performing VARTM in an autoclave on simple composite structures. The pressure of the inner chamber of the autoclave is reduced concurrent with the  
30 reduction of pressure within the VARTM tooling. A reduction of pressure in the autoclave results in zero net pressure across the tooling, significantly reducing the stresses on the tooling. A reduction in the stresses on the tooling allows the tool and cover to be constructed with relatively thin walls, which reduces the weight and thermal capacitance of the tooling. Reducing the weight of the tooling allows for  
35 easier handling of the tooling. Also, reduction of the thermal capacitance of the tool reduces the time needed to heat and cool the tool and composite structure.

U.S. Patent No. 5,015,168 to Boime et al. discloses tooling for use in VARTM that forms a somewhat more complex composite panel that includes a row of panel

5 stiffeners. The tooling includes a block, a sealing bag and calibration parts. The peripheral edge of the bag is connected to the block by a sealing bead and defines a tight volume. The panel is placed in the tight volume between the bag and the block. The calibration parts are placed outside the volume, above the bag and between the panel stiffeners to ensure maintenance of the geometry of the stiffeners during resin transfer. Despite the improvement in structural complexity of the resulting composite part, the use of soft tooling limits the precision to which details can be produced on the part using the process of Biome et al.

Notwithstanding the prior techniques for forming composite structures, it would be advantageous to have a further improved process for the production of complex composite structures to narrow tolerances that have sufficiently high fiber volumes to be used as primary structures on aircraft or marine vessels.

### SUMMARY OF THE INVENTION

The present invention addresses the above needs and achieves other advantages by providing a resin infusion mold tool system with vacuum assisted resin transfer molding that uses a subsequent pressure bleed to achieve high fiber volume fractions on complex composite structures. The mold tool system includes tooling having machined details that are positioned under a vacuum bag. Positioning of the machined details under the vacuum bag establishes a hard interface between the inner tooling and dry fiber preform. The hard interface allows for the formation of critical features within tight tolerances as the composite structure is being formed. In addition, the fiber volume fraction of the composite structure is increased from 54% to 57% or greater by the use of an additional bleed step in an autoclave.

In one embodiment, the present invention includes a mold assembly for distributing a resin throughout a dry fiber preform to form a composite structure. The mold assembly comprises an outer mold line tool which supports the dry fiber preform. An inner mold line tool is disposed on the dry fiber preform to form a hard interface between the inner mold line tool and a portion of the dry fiber preform. A vacuum bag encapsulates the inner mold line tool and forms an air-tight seal around the hard interface. A resin supply is connected in fluid communication with the dry fiber preform and supplies resin to the hard interface. A vacuum supply is connected in fluid communication with the mold assembly, supplies vacuum pressure to the hard

5 interface and draws excess resin away from the hard interface such that the composite structure is tightly toleranced at the hard interface after curing.

In another aspect, the mold details on the inner mold line tool are positioned at the hard interface to imprint the mold detail onto the composite structure. An external locating fixture rigidly fixed to the inner mold line tool through an opening in the  
10 vacuum bag positions the mold line tool within a tight tolerance of  $\pm 0.015$  inches or less. A mounting seal seals the opening in the vacuum bag against leakage of air when the vacuum is applied.

In another embodiment, a method for vacuum assisted resin transfer molding includes forming the resin transfer assembly by positioning the dry fiber preform on  
15 the outer tool. The inner tool is positioned on a portion of the dry fiber preform and sealed in the vacuum bag. The external locating fixture is attached through a hole in the vacuum bag to the inner tool thereby positioning the inner tool within a tight tolerance. The hole in the bag is sealed against airflow with the mounting seal. The resin transform assembly is then positioned in an autoclave. A resin inlet line and a  
20 resin outlet line are attached to the resin transfer assembly. The resin inlet line supplies liquid resin to the dry fiber preform. The resin outlet line is vacuum pressurized to bleed resin out of the fiber preform. The resin inlet line is detached and the autoclave door is shut. The autoclave is pressurized which bleeds additional resin out of the fiber preform resulting in a fiber volume fraction of 57% or greater.

25 The mold tool system and pressure bleed method of the present invention has several advantages. Large and complex fiber composite structures can be manufactured as a single piece, representing a significant cost and labor savings. The composite structure produced has a high fiber volume fraction allowing the large structures to be used in applications that experience large loads, such as airplane  
30 wings or marine structures. The hard tooling interface produces details and positions structural elements within relatively tight tolerances that are unavailable in conventional systems that use soft tooling.

#### BRIEF DESCRIPTION OF THE DRAWINGS

35 Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

5           Figure 1 is a perspective view of a mold tool assembly of one embodiment of the present invention;

          Figure 2 is a cross-sectional view of an inner mold line tool, of the mold tool assembly shown in Figure 1, covered by a vacuum bag;

          Figure 3 is an exploded view of the mold tool assembly shown in Figure 1;  
10       and

          Figure 4 is a schematic of pressure bleed of the mold tool assembly of Figure 1 in an autoclave.

#### DETAILED DESCRIPTION OF THE INVENTION

15           The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and  
20       complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

          The present invention allows for the construction of large fiber composite structures with inner mold lines having tight tolerances and intricate detailing by using hard tooling. In addition, the present invention uses a post bleed step in an  
25       autoclave to increase the fiber volume of the completed composite structure, lending the structure sufficient strength for use in the primary structures of aircraft, marine applications and the like.

          Figure 1 depicts a perspective view of a vacuum assisted resin transfer mold (VARTM) assembly **10** for use with a post bleed step in an autoclave **23**. The  
30       assembly **10** includes a first, or outer, mold line tool **11**, a plurality of second, or inner, mold line tools **12**, and an external locating fixture **13**. Figure 3 depicts an exploded perspective view of the assembly **10** showing a complex dry fiber preform **14** having a rectangular base **15** that serves as an outer mold line and also having an integrally stiffened inner mold line. The inner mold line of the dry fiber preform **14**  
35       comprises a plurality of stringers **16** extending lengthwise along the rectangular base **15** interconnected by a plurality of intercostals **17**.

          Assembled, the dry fiber preform **14** is disposed over a plurality of resin channels **19** on the surface of the outer mold line tool. The inner mold line tools **12**

5 are disposed on the stringers 16 and the intercoastals 17. The assembly 10 is placed  
in an autoclave 23 with an open door, as shown in Figure 4. The inner mold line tools  
12 are encapsulated in a vacuum bag 18 and a plurality of vacuum lines 24 are  
attached in fluid communication with the vacuum bag. A plurality of resin supply  
lines 25 are attached in fluid communication with the resin channels 19 of the outer  
10 mold line tool 11. The resin supply line 25 supplies resin to the channels 19 which,  
along with the pressure differential between the resin source (inlet lines) and the resin  
exit lines, (vacuum lines), distributes the resin into the dry fiber preform 14. This  
pressure differential is created by exposing the resin source (inlet lines) to  
atmospheric pressure and pulling a vacuum on the resin exit lines and subsequent  
15 mold tool cavity/part assembly. Once the dry fiber preform is filled with resin, the  
resin inlet line is then detached, the autoclave door is shut and the autoclave is  
pressurized to bleed additional resin out of the fiber preform 14.

The outer mold line tool 11 is a rectangular plate with the resin channels 19  
machined, cut or preformed into the upper surface of the tool on which the dry fiber  
20 preform 14 rests during resin impregnation. The outer mold line tool 11 preferably  
has dimensions (length and width) sufficient to support the entire dry fiber preform  
14. The resin channels 19 extend along the length of the outer tool 11 and in a  
parallel, spaced relationship in order to access the dry fiber preform 14 at several  
locations. As depicted in the cross-section of Figure 2, each resin channel 19 has a  
25 sufficient depth to allow the free flow of resin along the bottom of, and into, the dry  
fiber preform 14. Resin can be injected at one end of the resin channel, and the resin  
channel 19 is preferably high enough that the resin reaches the other end of the  
channel. Alternatively, resin can be injected at both ends of the channel, or at other  
points along the channel.

30 The outer mold line tool further defines a plurality of fixation holes 20 along  
its outer periphery and evenly spaced across the dry fiber preform for the rigid  
fixation of the external locating fixtures 13. The outer mold line tool 11 is preferably  
constructed of aluminum to provide light weight and rigidity. However, the outer  
mold line tool may be constructed of other materials such as other metals and  
35 polymers that can withstand the heat and pressure of the autoclave process.

The inner mold line tools 12 include a set of stringer molds 21 and intercoastal  
clip molds 22. Mold details can be on one, or both, sides of each stringer. The  
stringer molds 21 are on both sides of each stringer and define channels sized to cover

5 the stringers 16 of the dry preform 14 once assembled. The channel shape of each  
stringer mold 21 is split longitudinally to allow assembly onto the stringers 16 with  
subsequent attachment of the external locating fixture 13. The clip molds 22 are  
similarly constructed, but shorter in length to span the distances between the stringers  
16 and to cover the intercoastals 17. Preferably, the mold line tools are hard tooling,  
10 constructed of a material such as aluminum that forms a hard interface with the  
portions of the dry fiber preform 14. The hard interface results from direct contact of  
the hard inner tooling 12 with the preform 14 and, in cooperation with the external  
locating fixtures 13, allows for tight tolerances and details to be maintained during  
formation of the composite structure under pressure. If desired, a peel-ply (not  
15 shown), or other intervening layer, may be interposed between the mold line tools 12  
and the dry fiber preform when tight tolerances are not as crucial. The peel ply  
facilitates removal of resin flash on the outer mold line surface of the composite  
structure after cure.

The vacuum bag 18 is preferably constructed of silicone rubber and is sealed  
20 around its periphery to enclose the inner mold line tools 12 using tape (not shown),  
glue or other sealant if desired. Sealing the inner mold line tools 12 inside the  
vacuum bag 18 avoids softening the hard interface between the tools and the dry fiber  
preform 14 and affecting the ability of the tooling to hold a tight tolerance during  
resin infusion.

25 Although the inner mold line tools 12 are enclosed inside the vacuum bag 18,  
the external locating fixtures 13 are located outside the bag, as shown best in Figure 2.  
A through-the-bag attachment of the fixtures 13 to the tools 12 is accomplished  
through the use of a mounting seal assembly that includes a flanged insert 26, and a  
rubber vacuum bag interface 27 mounted on a bolt and washer assembly 28. The bolt  
30 and washer assembly preferably rigidly secures the external locating fixture 13 to the  
stringer molds 21 and the intercoastal clip molds 22 of the inner mold line tools 12.  
The bolt assembly 28 enters through a hole defined by the bag 18, passing through the  
flanged insert 26 and the rubber interface 27. The flanged insert 26 and rubber  
interface 27 are pressed together around the part of the bag 18 that defines the  
35 periphery of the hole by tightening of a nut on the bolt assembly 28 which forms an  
air-tight seal around the hole in the bag. The mounting seal assembly is used at every  
point where the bolt assembly 28 breaches the vacuum bag 18. The flanged inserts 26  
allow the location of a detail or plurality of details (i.e., the stringer molds and

5 intercoastal clip molds) through the soft vacuum bag **18** while maintaining vacuum integrity of the bag at pressures up to 100 psi.

The assembly **10** includes three external locating fixtures **13**, one for each row of intercoastals **17**. The external locating fixture **13** comprises a frame with a pair of spaced walls **29** that extend downward onto opposing sides of the intercoastal clip molds **22** and along each intercoastal row **17**. The spaced walls **29** are notched to allow clearance for the tops of each stringer mold **21**, as shown in Figure 1. A pair of the bolt assemblies **28** connect the opposite sides of each of the intercoastal clip molds **22**, securing the intercoastal clip molds to the pair of spaced walls **29** of the external locating fixtures **13**. Each of the outside pair of stringer molds **21** are secured to the three external locating fixtures **13** through a set of three bolt assemblies **28** located near the ends of the external locating fixtures. The inner three stringer molds **21** are secured by the interdigitation of the secured intercoastal clip molds **22** amongst the stringer molds **21**. As mentioned above, each of the external locating fixtures **13** is secured at its ends to the outer mold line tool **11** using pairs of the fixation holes **20**. Note that fixation of the fixtures **13** to the outer mold line tool **11** does not require the use of the flanged inserts **26** or rubber interface **27** because these connections are not through-the-bag connections. The external locating fixtures **13** and the hard inner mold line tools **12** precisely locate the molding details to within  $\pm 0.015$  inches, or even  $\pm 0.010$  inches, on large and complex composite structures.

25 The vacuum assisted resin transfer molding process is initiated by positioning the dry fiber perform **14** over the resin channels **19** of the outer mold line tool **11**. If desired, the peel ply is placed between the surface of the outer mold line tool **11** and the dry fiber perform **14**. The inner mold line tools **12** are inserted into the dry fiber perform **14** and the vacuum bag is placed over this assembly. The locating fixture **13** is secured to the outer mold line tool **11** and the vacuum bagged inner mold line tools **12**. The outer mold line tool **11**, inner mold line tools **12**, the locating fixture **13** and the dry fiber perform **14** are then positioned inside the autoclave **23**.

The autoclaving step of the VARTM pressure bleed process is shown schematically by Figure 4. The autoclave **23** includes a cylindrical container having a wall **30** sealed closed for pressurization using a door **31**. The resin transfer assembly **10** is placed inside the autoclave **23**. The vacuum lines **24** are attached to locations in the vacuum bag **18** as known to those of skill in the art and, for example, as described in U.S. Patents Nos. 4,902,215 to Seemann, III and 4,942,013 to Palmer et al. The



5 vacuum lines **24** pass through the autoclave wall **30** and are connected to an  
accumulator tank (pressure pot) **33** which is connected to a vacuum pressure source  
(not shown). The first ends of the resin supply lines **25** are placed inside a container  
of liquid resin **32** exposed to atmospheric pressure and the other ends of the supply  
lines are attached to ports **34** in the outer mold line tool **11** that feed the resin channels  
10 **19**.

With the autoclave door **31** slightly cracked open, the autoclave is used like an  
oven to heat up the resin transfer assembly **10**. Heating up the assembly optimizes the  
viscosity of the resin for infusion into the dry fiber preform **14**. A vacuum is pulled  
on the vacuum lines **24** creating a pressure differential which forces the resin out of  
15 the resin container **32** and into the inlet supply lines **25**. The resin, which is now  
evenly distributed over the outer mold surface, flows through the thickness of the dry  
fiber preform **14** and exits out the vacuum lines **24** attached to the vacuum bag **18**.  
The resin flows out of the vacuum lines **24** and into the accumulator tank **33** where it  
is collected. As the tanks fill up, the collected resin is either periodically dumped by  
20 hand or automatically recycled back to the resin container **32** via a transfer pump (not  
shown). The continuous flow of resin through the part is maintained until the  
assembly **10** is completely filled with resin.

Once the preform is filled with resin, the vacuum is reduced to stagnate resin  
flow, the resin supply lines **25** are closed off and the autoclave door **31** is then closed  
25 and locked. The autoclave **23** is then pressurized, squeezing the now resin-  
impregnated fiber preform **14** to bleed off the excess resin through the vacuum lines  
**24**. The vacuum lines **24** are then closed off and the pressure inside the autoclave **23**  
is increased further. Preferably, the pressure ranges between 0 and 100 psi of  
autoclave pressure. The temperature inside the autoclave is then increased to cure out  
30 the fiber panel **14** resulting in a composite structure that has a much higher fiber  
volume fraction of 59% versus 54% for conventional processes. The assembly **10** is  
removed from the autoclave **23** and the vacuum bag **18** and inner mold line tools **12**  
are subsequently removed from the completed composite structure. The peel ply can  
also be removed, taking with it flashing material remaining after the pressure bleed  
35 step. In the illustrated embodiment, the VARTM pressure bleed process results in an  
integrally stiffened panel that is 2.28 meters long and .9 meters wide, although panels  
or parts having other shapes and sizes can be similarly fabricated.

5           Many modifications and other embodiments of the invention will come to  
mind to one skilled in the art to which this invention pertains having the benefit of the  
teachings presented in the foregoing descriptions and the associated drawings. For  
instance, in lieu of a supply of liquid resin, a resin film could be disposed on the dry  
fiber preform and heated to distribute the resin throughout the preform. Therefore, it  
10 is to be understood that the invention is not to be limited to the specific embodiments  
disclosed and that modifications and other embodiments are intended to be included  
within the scope of the appended claims. Although specific terms are employed  
herein, they are used in a generic and descriptive sense only and not for purposes of  
limitation.